Buckling Strength in Carbon Fiber Polymer Matrix Composites Produced by Filament Winding for Structural use in Rockets

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Abstract

High-powered rockets use thin walled carbon-fiber reinforced polymer (CFRP) tubes as the primary structure and the tubes experience compressive stress during flight, which is estimated at 18MPa. Cal Poly Space Systems (CPSS) recently acquired the capability to use filament winding for manufacturing CFRP structures. Filament winding wraps carbon-fiber tow coated in epoxy around an axisymmetric object, and in this case, an aluminum cylinder. The tube laminate is an angle-ply orientation testing the winding angles 35°, 50°, 65°, and 80° and winding patterns 1/1 and 8/1 in combination using an unsupported parallel compression test. Coupons are one-inch in height, 2.5 inches in diameter and fail in buckling. Resulting test data from an Instron 5584 Mechanical Testing Machine generate stress-strain curves and the curves determine laminate modulus and maximum strength. Statistical comparisons are between adjacent winding angles within a pattern and between winding patterns with the same winding angle. Laminate modulus and max strength increase as the winding angle increases due to the angle-ply orientation of the laminate. Five of the eight total B-basis values exceed the required maximum strength of 18MPa. Adding a 90° lamina around a tube’s circumference would significantly improve maximum tube strength and stiffness.

Key words: filament winding, carbon-fiber polymer matrix, compression testing, buckling, high-powered rockets

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1. Introduction

Cal Poly Space Systems (CPSS) is a California Polytechnic State University (Cal Poly) engineering club focused on designing, building and launching rockets. These rockets are made of polymer-matrix composites (PMC) such as glass or carbon fiber with an epoxy matrix. Currently, CPSS constructs body tubes (thin walled composite cylinders) by wrapping woven fiber fabric around a PVC pipe. This method works well because it is a well-established method within the club and produces parts that are suitable for most applications. The interest in filament winding became present due to wanting to build larger hybrid rockets. Hybrid rockets consist of one-part liquid and one-part solid, commonly with a liquid oxidizer contained in a tank under high pressure and the solid as the fuel. To achieve the required burn times for longer flights to reach higher altitudes, the rocket needs larger tanks or tanks with higher pressure and both cases increase the amount of the material required for tank to contain the oxidizer. Filament winding enables the use of composite overwrapped pressure vessels (COPV), but the current knowledge in the club is minimal about the filament winding process. This project is investigating the characteristics of filament wound parts as the structure of a high-powered rocket to increase CPSS’s understanding of the process to allow future projects to utilize the manufacturing method.

1.1. High-Powered Rocket Design

High-powered rocketry is commonly practiced by amateurs and universities. The rocket design used in this project is based around high-powered rockets built from scratch by CPSS. “High-powered” refers to rockets that use motors excess of 160N·s of impulse [1]. CPSS high-powered rockets use motors ranging from H sizes to J sizes, reach an altitude of two thousand to five thousand feet and travel at speeds below Mach 1, usually around Mach 0.6. Physical dimensions of these rockets are around 2.5 inches in diameter, range between 3 and 4 feet in length, and range from 1.3kg to 2.2kg in weight.
Figure 1 is an illustration showing basic forces and stresses on a rocket traveling through the atmosphere. These forces and stresses are only estimations and used to get a general idea of structural requirements.

If the nosecone is the top of the rocket and the fins are at the bottom, the region between the two is the body tube that functions to contain all the parts of the rocket and to provide the required strength and stiffness needed for a successful flight. Atmospheric drag acts on the nosecone with all the force transferring to the body tube, in the opposite direction of the thrust produced by the motor. The body tube contains the motor, producing thrust, and pushing on the body tube, propelling the rocket. Since the forces are opposite on either end, the body tube is under compression and the magnitude of the compression stress is directly related to the magnitude of the drag force. An assumption for this report is that nosecone shapes or other parts of the rocket will not affect the drag force, $D_f$, in order to simplify aerodynamic analysis.

Drag on a high-powered rocket is determined using Eq. (1):

$$D_f = \frac{1}{2} \rho V^2 C_d A$$

Where $\rho$ is the atmosphere density, $V$ is the velocity, $C_d$ is the drag coefficient, and $A$ is the cross-sectional area [1]. Atmospheric density is assumed constant for an H-size high-powered
rocket. The biggest factors affecting magnitude of $D_f$ are the speed at which the rocket is traveling and the cross sectional area in the direction of travel.

If a rocket’s mass is 1.007 kg and uses an Aerotech H123W motor producing 123 N of thrust, the rocket will reach a maximum velocity of 220 m/s [2]. Finally assuming a drag coefficient of 0.75, the drag force is 75.6 N. Previously built body tubes generally have a wall thickness of 0.045 inches, resulting in a maximum compression stress ($\sigma$) on the structure of 18.4 MPa found using Eq. (2). The variable $F$ the applied load and, $A$, the cross sectional area of the tube, is determined with Eq. (3). The inner and outer diameters are represented as $d_1$ and $d_2$

$$\sigma = \frac{F}{A} \quad (2)$$

$$A = \frac{\pi}{4} (d_1^2 - d_2^2) \quad \text{where} \quad d_2 = d_1 - 2t \quad (3)$$

respectively, and $t$ is the wall thickness. For this report, a CFRP tube must have a compressive strength that exceeds 18.4 MPa.

In the future, CPSS wants to build a rocket 10 inches in diameter to reach 60,000ft carrying a 30kg payload. Since $D_f$ is a function of area, and assuming everything else remains unchanged, increasing the cross-sectional area will increase the magnitude of the drag force, causing the stress on the body to increase significantly (Figure 2). The stress experienced by a ten-inch

![Figure 2](image.jpg)

*Figure 2: As thrust increases, rockets increase in size and weight, keeping the velocity a similar magnitude.*
diameter rocket will increase to 370 MPa. This aerodynamic model is simplistic, but the values of strength are an estimate of the stress experienced by a high-powered rocket. Composite materials become more appropriate for a rocket body tube due to the high specific strength and high specific stiffness.

1.2. Polymer Matrix Composites

Polymer matrix composites (PMC) are a type of composite material consisting of high strength fibers, typically ceramic fibers, held together by a polymer matrix. The main advantage of PMC materials is the high strength to weight ratio and high stiffness to weight ratio, or high specific strength or high specific stiffness. PMC materials get their strength from the ceramic fibers while matrix contributes relatively little to the overall strength and stiffness of the composite part. PMC’s are anisotropic due to the different material properties in different directions. Designers can take advantage of the anisotropic nature of the PMC material by tailoring the properties of the part to the intended application.

One of the simplest methods for fabricating composite parts is by performing a hand layup where a person is manually manipulating the PMC materials. To cure the composite, vacuum bags and autoclaves compress and heat the composite part. This process is useful for complicated geometries, but is slow and requires large amounts of labor. This report investigates filament winding as a method to fabricate carbon fiber reinforced polymers (CFRP) and to obtain material properties of tubes produced by this method. Filament winding is an alternative method for simpler parts and reduces required labor. Section 1.3 covers filament winding in more detail. As with many other applications, PMC materials high specific strength and high specific stiffness enable structures with lower weight. For a rocket, this means a higher achievable altitude and an increased payload capability.

1.2.1. Carbon Fiber

Carbon fiber is one of the two commonly used ceramic fibers in polymer matrix composites used today. The fibers start from either petroleum pitch or polyacrylonitrile (PAN) precursor then are put through a series of steps heating and stretching the precursor polymer transforming it into the
final graphite state. High temperatures convert the structure from a hydrocarbon into graphite by removing most of the non-carbon elements present in each precursor. Different amounts of heat and stretching influence the final fiber properties and produce a range of properties [3].

The diameter of a single fiber is on the scale of one micrometer and is bundled with other fibers into a continuous spool called tow. From tow, the fibers can be weaved into fabric, or chopped into short fibers, and each fiber form has its uses and is used in various composite manufacturing methods[3],[4]. The fiber type and the number of fibers classify tow. For example, if the tow has 15,000 fibers bundled together, a short hand way to describe it is calling it “15k tow”. Each carbon fiber producer will use a different method of naming their products, but each company will differentiate between the different types. The fibers can be twisted or untwisted in a bundle and different manufacturing processes use both bundle forms depending on the machine configuration.

1.2.2. Epoxy

A common matrix material used in PMC materials is epoxy since it starts as a liquid and cures to a solid and its desirable properties especially for aerospace applications. Epoxy is a thermoset polymer, commonly starting as two separate compounds: bisphenol-A as the resin and a curing agent. The curing agent, or hardener, can come in many forms and is a way to tailor the properties of epoxy; however, a common curing agent is diethyl-triamine (DETA)[4],[5]. Bisphenol-A contains the epoxide groups and DETA reacts with those groups forming a three-dimensional cross-linking network. Figure 3 shows the general reaction of epoxide molecule in the resin and amines in the curing agent to form a cured epoxy molecule [5]. The density and number of cross-links between molecules is the main factor in determining the properties of the solid epoxy.
Pre-impregnated composite materials, or prepreg for shot, are composite materials in the B-Stage, or the temperature low enough that significantly reduces the rate of cross-linking, allowing for the storage of composite material with epoxy already coating the fibers. An alternate method to prepreg called a wet layup is applying liquid epoxy to dry fibers immediately prior to forming the prepreg into a part. Wetting is a term used to describe the tendency for a resin to coat the fibers in a wet layup. Incomplete wetting will lead to regions of dry fibers absent of the matrix, reducing the overall properties of the part and usually acting as an initiation site for failure. Epoxy has a workable time limit called the pot life, describing the time where crosslinking is occurring, but the density of cross-links is low enough that the viscosity of the liquid is relatively unchanged. At the end of the pot life, viscosity increases significantly, reducing the wetting of the fibers and ability of the epoxy to adhere to other lamina. Pot life is important for wet filament winding because the epoxy must remain a low viscosity long enough for sufficient wetting of the fibers.

1.3. Filament Winding Background

Filament winding is the process of fabricating composite structures by placing continuous fibers (filament) over a rotating mandrel in a controlled and specified manner [4]. Winding angle \((\theta)\) and winding pattern are primary factors controlling the properties of filament wound structures. Ideal geometries for filament winding are axisymmetric shapes without concavity; however, multi-axis machines can wrap more complex geometries such as pipe bend at 90°.
The filament must travel in multiple directions, once the filament traverses the mandrel in one direction, the fibers need to change direction and return in the opposite direction. On either end of the part (the region desired winding angles and patterns), there needs to be some form of turn around zones for the filament to change direction. This can be simply a strait section gradually allowing the machine to change the angle of the filament from $+\theta$ to $-\theta$ while maintaining proper fiber tension. Figure 4 shows a generic filament winder using hemispheres as endcaps instead of a strait section. The carriage holds the payout eye that controls the fiber angle relative to the mandrel. Just before the payout eye, the fibers pass through a resin bath in a wet winding configuration coating the dry fibers in the matrix material. Figure 5 is a picture of a complete wrapped COPV made with filament winding.
1.3.1. Winding Angle

Winding angle describes the filament angle relative to the mandrel during winding (Figure 6). The range of angles is 0° and 90° where 0° is along the longitudinal direction and 90° is along the transverse direction. Winding angle serves a similar purpose as fiber orientation in a thin plane orthotropic lamina and influences the properties of the tube in a similar manner [4]. For example, if the tube were unrolled into a flat plane, the fiber orientation would be the same angle as the winding angle.

1.3.2. Winding Pattern

Winding pattern influences the sequence of fiber placement and the frequency of the fibers crossing previously laid paths. Winding angle influences which patterns are possible, but other parameters such as length can influence the pattern as well. The way CADWIND (specialized CAD software for generating filament-winding paths) denotes winding pattern is with two numbers separated by a forward slash, for example, 5/1. Figure 7 uses patterns 5/1 and 5/2 to illustrate what each number influences in the pattern [6]. If looking at a cross section of the mandrel, the filament path forms a “five pointed star” as it crosses through each point without
skipping a number by proceeding sequentially one through five. The “5” is the amount of times the filament must pass over one end of the mandrel before the pattern repeats until there is full coverage. Each repeat shifts the pattern around the rotation axis by one width of the filament. The skip parameter is the “1” and “2” after the forward slash. A skip parameter of “1” means the pattern does not skip any points, but a skip parameter of “2” will pass through every other point until the filament passes through each point. Even though the five-pointed star is present in both, the pattern is slightly different and can affect the mechanical properties of the tube [7].

1.4. Compression Strength in Composites

This project will be testing samples in compression loading because compression is the primary stress condition on a high-powered rocket during flight. Under compression, the matrix will have a higher influence on the strength, but the matrix still functions as a medium to keep the fibers in the intended directions [5]. Composite structures manufactured using filament winding have a unique pattern where fibers are interlaced due to the roving crossing over previous fiber paths, but it is not quite the same as a weave pattern in carbon fiber cloth. The characteristic looks is a rhomboid unit cell as shown in Figure 8 where a triangular ‘mosaic’ is composed of the winding angle $\theta$ alternating between $+\theta$ and $-\theta$. A single layer produced by filament winding is two lamina interlaced together. Mathematical analysis can model a single layer produce by a filament winder as a two-ply laminate with one ply $+\theta$ and the other ply $-\theta$.

Figure 8: The rhomboidal shape primarily determined by the winding pattern [7].
Since longitudinal, continuous fiber PMC’s exhibit a significant difference between the elastic modulus of the matrix and fibers, compressive failure is primarily due to localized buckling of fibers. If the matrix behaves elastically, elastic microbuckling will be the primary failure mode, or if plastic deformation occurs, fiber kinking will be the primary failure mechanism. The epoxy matrix is assumed to only deform in the elastic region before failure due to the presence of stiff fibers preventing plastic deformation [8]. In the elastic case, fibers will experience two types of elastic microbuckling: extension microbuckling at low fiber volume fractions or shear mode of buckling occurring at high fiber volume fractions. Figure 9 is an example of extension microbuckling and buckling due to shear. Of the two failure modes, shear mode is more common because most PMC’s have high fiber volumes and shear buckling occurs at higher volume fractions (greater than 30% fiber volume). Shear occurs between the fiber and matrix since the fiber wants to slide past the matrix. The compressive strength can be predicted using Eq. (4) which is a relationship between the matrix shear modulus, $G_m$, and the fiber volume fraction, $v_f$ [5],[9].

$$\sigma_{Lcu} = \frac{G_m}{1 - v_f} \quad (4)$$

This relationship is true regardless of fiber type, since only the material properties of the matrix and the volume fraction of the fibers affect the strength. Compressive strength will increase as $v_f$ increases. On a smaller scale in the PMC, the fiber has a large length to diameter ratio resulting in a low stability. The matrix is resisting the buckling of the fibers under load. The shear strength between the matrix and the fiber is responsible for maintaining the fiber orientation.
Eq. (4) holds true when the lamina itself is not buckling. Buckling is a type compressive failure of members. While Compressive strength is independent of geometry, but buckling incorporates geometrical stability into the failure. Length, diameter and material all affect buckling, the maximum load will decrease as the length of the member increases. Buckling failure occurs at a critical load and occurs suddenly [12].

Other investigations into the effect winding angle on compressive strength of carbon fiber PMC’s and found that angles closer to 0° showed higher strength [10]. With composite lamina experiencing tensile loading, a general trend is strength decreases as fiber angle increases away from the longitudinal direction. Jia et al. reported that winding angles of 20°, 60°, and 80° are higher strength than 40°. Figure 10 is a graph of the study’s data showing the compressive strengths and compressive modulus at the four selected winding angles [10]. Their explanation for why different winding angles showed different modes of failure. The 20° winding angle failed in primarily brittle fracture, 60° and 80° angles failed primarily in transverse shearing and 40° angle exhibited failure primarily with local buckling of the fibers. This report does not investigate the failure modes of different winding angles, but failure modes of a PMC composite could be an area of future investigation.

Previous work done with the filament winder used in this experiment produced a plastic bottle overwrapped in carbon fiber to test the capability of a pressure vessel made with the machine. Using the same machine as this report, the experimentally tested fiber volume was 50.75% matrix and 49.25% fibers. The reported fiber properties were lower than the values reported in
the product data sheet published by the fiber manufacturer. There is some doubt in the reported properties of the fibers since the samples used to test for the fiber strength were poorly labeled and were potentially mixed up [11].

1.4.1. Buckling in Laminates

Using Classical Laminate Theory (CLT) stiffness can be calculated using Eq. (5) – (22) and material data based on published product data for both the epoxy and filament. CLT equations only account for winding angle and assume the laminas are two distinct layers with the mid plane through the diameter of the tube. Figure 11 shows a cross-section of a thin walled tube, exaggerating the wall thickness, and shows how the lamina is symmetrical. The distance from the mid-plane to the first lamina mid-plane, $h_1$, is the radius plus half the lamina thickness. The second lamina distance, $h_2$, is an additional lamina thickness more than $h_1$.

Eq (5) - (9) determine Poisson’s ratio in the fiber and transverse direction, $\nu_{12}$ and $\nu_{21}$ respectively, elastic modulus in the same directions, $E_{11}$ and $E_{22}$ respectively, and the shear modulus, $G_{12}$ of a lamina. Material property values are obtained from product data sheets for Hexel IM2A-12K carbon fiber tow and FibreGlast 2000/2120 epoxy[13],[14]. The fiber Poisson’s ratio, $\nu_f$, equals 0.2 and the matrix Poisson’s ratio, $\nu_t$, equals 0.265. The elastic modulus for the fiber, $E_f$, equals 276 GPa and the epoxy elastic modulus, $E_t$, is 2.89 GPa. Figure 12 uses a fiber volume fraction, $V_f$, equal to 50%. $G_f$ and $G_t$, the shear modulus’ for fiber and matrix respectively can be calculated using Eq. (10).

$$\nu_{12} = \nu_f V_f + \nu_t (1 - V_f) \quad (5)$$

![Figure 11: Cross-section view of a tube with the mid-plane through the diameter of the tube. This makes the tube symmetrical.](image)
\[ E_{11} = E_f V_f + E_t (1 - V_f) \]  
\[ E_{22} = \frac{E_f E_t}{E_f (1 - V_f) + E_t V_f} \]  
\[ G_{12} = \frac{G_f G_t}{G_f (1 - V_f) + G_t V_f} \]  
\[ \nu_{21} = \frac{E_{22}}{E_{11}} \nu_{12} \]  
\[ G = \frac{E}{2(1 + \nu)} \]

Q matrix is calculated using Eq. (11) - (15) based on material properties previously calculated.

\[ Q_{11} = \frac{E_{11}}{D} \]  
\[ Q_{21} = \frac{\nu_{12} E_{22}}{D} \]  
\[ Q_{12} = \frac{\nu_{21} E_{11}}{D} \]  
\[ Q_{22} = \frac{E_{22}}{D} \]  
\[ Q_{66} = G_{12} \]

Where \( D = 1 - \nu_{12} \nu_{21} \)

\[ \overline{Q} \] matrix for each lamina, one at +\( \theta \) and the other at −\( \theta \), is found using Eq. (16) - (21)

\[ \overline{Q}_{11} = Q_{11} t^4 + 2(Q_{12} + 2Q_{66})u^2 t^2 + Q_{22} u^4 \]  
\[ \overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})u^2 t^2 + Q_{12} (u^4 + t^4) \]  
\[ \overline{Q}_{22} = Q_{11} u^4 + 2(Q_{12} + 2Q_{66})u^2 t^2 + Q_{22} t^4 \]  
\[ \overline{Q}_{16} = (Q_{11} - Q_{22} - 2Q_{66})u^3 t + (Q_{12} - Q_{22} + 2Q_{66})u^3 \]  
\[ \overline{Q}_{26} = (Q_{11} - Q_{22} - 2Q_{66})u^3 t + (Q_{12} - Q_{22} + 2Q_{66})u^3 \]  
\[ \overline{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{66})u^2 t^2 + Q_{66} (u^4 + t^4) \]

Where \( u = \sin(\theta) \) and \( t = \cos(\theta) \)
Once calculating $\overline{Q}$ at $+\theta$ and at $-\theta$, $A$, the stress-strain matrix of the laminate, can be calculated using Eq. (22) for each entry into the $A$-matrix:

$$A_{ij} = \sum_{k=1}^{k=2} (\overline{Q}_{ij})_{k} (h_{k} - h_{k-1})$$

The $A_{11}$ direction of the cylinders in this report is along the longitudinal direction of the cylinder. This is the same direction as the axis of rotation, and the axis experiencing load during a flight. The $A_{22}$ direction is the radial direction of the cylinder, perpendicular to the loading direction, but this direction is important to the buckling strength of a cylinder.

Figure 12 is a plot of calculated stiffness in the $A_{22}$ direction changing the angle at $1^\circ$ increments from $0^\circ$ to $90^\circ$ with the laminate in an angle-ply orientation. $A_{22}$ changes in a non-linearly, with a greater change from $0^\circ$ to $40^\circ$ than from $40^\circ$ to $90^\circ$. This change can be attributed to the angle-ply laminate orientation. General bucking of a thin walled, isotropic cylinder will cause the walls to bow outwards, decreasing in longitudinal length and becoming wavy along the tube walls. Fibers perpendicular to the loading direction increase buckling strength by improving the stability of the thin walls, allowing the buckling limit to reach the compressive limit of the material.
2. Problem Statement

Cal Poly Space Systems has the capability of filament winding for PMC materials, but has little analysis or understanding of PMC’s produced using this process for structural applications. Prior work with the process has shown its viability for producing COPV’s, but requires more analysis and more understanding of the process. To address the problem, this project will investigate the relationship of winding angle and winding pattern on PMC strength by mechanically testing the buckling strengths of carbon-fiber PMC’s produced using the CPSS filament winder. Buckling strengths can guide future designs for rocket structures and provide a better understanding of filament winding.

3. Experimental Procedure

CFRP tubes were manufactured using a Composites Machine Company (CMC) Computer Numerical Controlled (CNC) Filament Winder using dry Hexel IM2A 12K carbon fiber tow and FibreGlast 2000/2120 epoxy. The machine utilizes spindle rotation and Z-axis carriage movement parallel to the mandrel. Figure 13 shows the mandrel and carriage of the machine, and labels major parts of the machine. Tow unrolls from the fiber spool and passes through a series of rollers including one roller partially submerged in epoxy in the resin bath, subsequently coating the tow. Once coated, the tow passes over the tensioning system that keeps constant tension throughout a winding program. The tow angle and orientation is controlled by the payout eye while the tow is wrapped around the mandrel. The payout eye is polished plain carbon-steel
and two-inches inner diameter. The CNC controller synchronizes the carriage movement and mandrel rotation specified by the program file. Filament originated from the same spool for each tube and weighed before and after each tube winding. Tubes rotate at a slow rate until reaching the epoxy pot life then fully cure for 24 hours horizontally on the mandrel without rotating.

3.1. Winding Path Modeling and Generation

The CAD software program used for simulation and for code generation is CADWIND V9 version 9.2.11.1. Paths are a non-geodesic helical-type winding path using a friction factor of 0.1. Non-geodesic incorporates fiction between the filament and the mandrel into calculation for machine movement for the purpose of reducing slippage during winding. Filament slippage is one of the possible errors to occur during winding. The mandrel is a simple circular cross-section model with a 2.5-inch diameter and at least 12 inches for the tube length. The final tube length incorporates the part length with the desired winding angle and pattern and strait turnaround zones where the filament changes directions.

The turnaround zone on either end are a maximum 14-inch strait sections the same diameter as the mandrel. CADWIND generates machine code using the built in post processing capability and saves the code as a text-file readable by the winder’s computer.
3.2. Mandrel Preparation

The mandrel is an extruded aluminum tube 2.5 inches in outer diameter and about 9 feet in length. For the winder used in this project, a long mandrel enabled smaller winding angles since the length dictated the amount of carriage travel. Figure 14 shows how the mandrel is prepared before each winding. The mandrel was initially sanded and polished using sand paper and Mother’s Aluminum Polish. Any instance of polishing again is done using the same materials. The surface was cleaned using 70% isopropyl alcohol (IPA) between polishing and applying the release layers. The first layer is SC Johnson’s Paste Wax, it fills scratches and works as a minor mold release agent. The second layer, white lithium grease, reduces friction between the cured composite and the mandrel, which is important for removing cured tubes. The third and fourth layers are polyvinyl-alcohol (PVA) and serve as the primary mold release. These materials are readily available, easy to obtain, and inexpensive.

3.3. Tube Removal

After winding and curing, the whole mandrel cools in a freezer to 10°F to take advantage of aluminum’s higher coefficient of thermal expansion relative to CFRP. A collar on the mandrel pushes against the built up ends of the tubes. The tubes slide off due to lower frictional stresses from to the smaller, cold mandrel and the lubrication from the grease.
3.4. Coupons

Turnaround zones and coupons are cut off using a water lubricated abrasive-cutting saw. Coupons are cut at 1-inch increments from the desired winding section. The inner diameter of the tube is wiped with a wet paper towel to remove residual grease and PVA. As best as possible, ASTM E2954–15 was followed and specifics a 1-inch coupon height.

Since winding angle and winding pattern are the major parameters for a filament wound tube, tubes of four different winding angles, 35°, 50°, 65°, and 80°, and two different winding patterns, 1/1 and 8/1, were made and tested for a total of eight possible combinations. All sample groups each had one tube and every coupon was cut from the same tube. At least five coupons were tested per group. The rim of each coupon was sanded to remove stray fibers and to improve the quality of the edge, in an attempt to reduce bearing surface failures.

3.5. Compression Testing

Testing was on an Instron 5584 mechanical testing machine using an aluminum parallel plate compression fixture (Figure 15). On each aluminum bearing surface were two ¼ inch steel plates with a layer of fiber glass bonded to the surface. The fiberglass mitigates failure at the bearing surface.

![Figure 15: The compression test fixture is a simple parallel plate without any sample support. The top plate has a ball joint to allow the top plate to lay flat on a nonparallel test coupon.](image)

Applied Load
Top Part of the Fixture with a Ball-Joint
Test Coupon
Bottom Bearing Plate
faces on the test coupon, and force failures (buckling or otherwise) in the wall of the test coupons. The top plate of the fixture is a ball joint allowing the plate to pivot on account of non-parallel bearing surfaces. The ends of the sample are not supported by the fixture.

The center of the test fixture was located using a simple jig that referenced the same corner each test. ASTM E2954–15 was followed as much as possible during testing and the specification suggests constant crosshead movement at 3mm per minute. The testing machine measured strain based on cross-head movement and measured force with a load cell. Coupons were tested past the maximum buckling strength and the test was stopped manually.

4. Results and Discussion

Every sample failed in two different modes of bucking and pictured in Figure 16. The primary failure mode for most winding angles is the coupon wall bowing outwards from the center, forming a half-wave shape, and other failure mode in the 80° samples is kinking or folding along the fiber direction. Once unloaded, many of the samples return to their original geometry, but with a noticeable remnant of the buckling in the sample wall. Other test coupons show visible fractures in the walls. Table I lists each sample group’s average load and the standard deviation, and Table V in Appendix 8.2 lists the load of each coupon.

Figure 16: Picture a) is a sample loaded past the buckling limit showing a large half-wave buckle (the arrow points to the sample) and picture b) is kinking along the fiber direction of the 80° 1/1 sample. Both samples are 1 inch in height, 2.5 inches in diameter.
Table I: Summary of Maximum Loads

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>1/1</td>
<td>1/1</td>
<td>1/1</td>
<td>1/1</td>
</tr>
<tr>
<td></td>
<td>8/1</td>
<td>8/1</td>
<td>8/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Average (N)</td>
<td>497.80</td>
<td>1391.17</td>
<td>1667.69</td>
<td>3231.41</td>
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<td></td>
<td>676.39</td>
<td>2991.31</td>
<td>1536.37</td>
<td>5169.24</td>
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<tr>
<td>Standard Deviation (N)</td>
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<td>158.37</td>
<td>137.43</td>
<td>167.39</td>
</tr>
<tr>
<td></td>
<td>29.41</td>
<td>203.47</td>
<td>321.37</td>
<td>522.70</td>
</tr>
</tbody>
</table>

Data from the mechanical testing machine is in the form of load vs extension and the following calculations produce stress vs. strain curves. Axial compression stress ($\sigma$) and cross-sectional area ($A$) are calculated using the same equations that found required stress for a high-powered rocket body tube, Eq. (2) and Eq. (3) respectively. Strain, specifically % compression (the opposite of % Elongation), can be found using Eq. (23) where $x$ is the instantaneous compression and $x_o$ is the initial height of the test coupon.

$$\% \text{ compression} = \frac{x}{x_o} \quad (23)$$

Calculating $\sigma$ and % compression generate stress-strain curves for every test coupon and since crosshead movement occurred at a constant rate, an average at each time increment forms an average stress-strain curve for each sample group (Figure 17). These curves are approximate

![Figure 17: Stress-Strain curve for the sample group 35° 1-1 showing data starting at 0.1mm of compression until the maximum stress achieved by each test coupon. All groups follow the same general trend.](image_url)
stress-strain curves since strain was not directly measured on the test coupons, but based on crosshead movement on the machine. The initial non-linear section is the tube’s bearing surface completely contacting the test fixture surface and the fiberglass-epoxy layer. The linear region is compression of the coupon before buckling occurs, once buckling occurs, deformation changes to be non-linear until the curve ends as the maximum strength. The transition from linear compression to non-linear bucking is the yield point. The graph does not reveal a trend around the different combinations of angle and pattern. Patterns are not grouped in one region of the graph and neither are winding angles. Shapes of the curves do not match other curves with the same winding angle or winding pattern. Table II lists the average maximum stress of each sample group and standard deviation. The required strength is greater than 18.4 MPa, and six of the eight sample groups are valid options in a high-powered rocket body tube.

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>1/1</td>
<td>8/1</td>
<td>1/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Average (MPa)</td>
<td>13.43</td>
<td>34.93</td>
<td>49.57</td>
<td>66.53</td>
</tr>
<tr>
<td>Standard Deviation (MPa)</td>
<td>0.91</td>
<td>5.74</td>
<td>5.28</td>
<td>7.52</td>
</tr>
<tr>
<td>B-basis (MPa)</td>
<td>10.32</td>
<td>15.38</td>
<td>31.58</td>
<td>40.89</td>
</tr>
</tbody>
</table>

The last row in Table II is the B-basis of the sample groups, a suggestion from MIL-HNBK-17 for PMC property values and is a point on a normal distribution curve indicating 90% of the population is equal to or larger than the value [15]. The is only true for normally distributed data, and each sample group follows a normal distribution based on Anderson-Darling normality tests. Equation (24) calculates the B-basis using the sample mean, $\bar{x}$, and sample standard deviation, $S$.

$$B_{\text{basis}} = \bar{x} - k_B \times S$$  \hspace{1cm} (24)

$S$. Sample mean is multiplied by the constant, $k_B$, and, this constant is a function of the sample size that decreases as sample size increases. Paired t-tests between adjacent winding angles (for example 35° and 50°) and between winding patterns, all showed a statistical difference with 95% confidence comparing each group’s B-basis number. Sample groups are different and the combinations of winding pattern and winding angle affect the compression strength of the test coupons.
For a visual comparison, Figure 18 plots B-basis strength on the y-axis and groups each sample by winding angle along the x-axis. Winding pattern 8/1 exhibits higher strengths across all winding angles relative to winding pattern 1/1. Low fiber overlap of winding pattern 1/1 means large unidirectional regions of the laminate exists, however more overlap constricts fiber movement in the laminate, improving the physical stability, and ultimately the buckling strength. Large unidirectional regions allow fibers to fold and move easier, reducing microbuckling resistance of the individual lamina. Micromechanics of composite materials says smaller winding angels should exhibit stronger compression strengths, and remains true if buckling does not occur in the lamina. Once buckling occurs, geometric stability due to laminate the properties will influence the strength instead of micromechanics in a single ply. Strait, continuous PMC materials are anisotropic, and an angle-ply stacking sequences result in unequal properties along the x and y directions. These directions correspond to the longitudinal and radial directions respectively. Increasing winding angle leads to increasing strength since fibers are aligned in a more favorable direction for improving buckling strength.

Comparing experimental stiffness to calculated stiffness shows the significance of an angle-ply stacking sequence. Experimental stiffness is simply the slope of the linear region of the stress-strain curve in the coupon’s stiffness. Table III lists average, B-basis, calculated stiffness values, and corresponding standard deviations. Table VII in Appendix 8.2 lists stiffness values for each test coupon.
Table III: Stiffness of Each Sample Group

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>1/1</td>
<td>8/1</td>
<td>1/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Average (MPa)</td>
<td>6.95</td>
<td>23.98</td>
<td>25.54</td>
<td>22.48</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.28</td>
<td>3.80</td>
<td>0.92</td>
<td>2.39</td>
</tr>
<tr>
<td>B-basis (MPa)</td>
<td>2.60</td>
<td>11.01</td>
<td>25.54</td>
<td>14.34</td>
</tr>
<tr>
<td>Calculated (MPa)</td>
<td>8.36</td>
<td>14.67</td>
<td>31.12</td>
<td>27.27</td>
</tr>
</tbody>
</table>

Stiffness was calculated using Eq. (5) - (21) with experimental fiber volumes listed in Table IV in Appendix 8.1. Fiber volume is obtained from measuring weight of tow used and final tube weight then converting weights to volumes using the manufacturer’s published densities for the fibers and the epoxy. Fiber volume with this method is close to fiber volume in previous work with the same filament winder and materials [11]. The method of calculation in this report only accounts for fiber angle, assuming weave pattern or winding pattern lacks influence on the final stiffness. Experimental data shows pattern has an effect, but the calculated values of stiffness are similar.

Figure 19 plots average values and calculated stiffness for each sample group to show a visual comparison between the calculated values and experimental data. The trend is similar to that in Figure 18 where pattern 8/1 is stiffer at every angle compared to pattern 1/1, and stiffness

![Graph](image_url)  
*Figure 19: Mean stiffness values compared to calculated stiffness in the A22 direction. Volume fraction is based off experimental data for each angle.*
increases as winding angle increases. Superimposing calculated stiffness onto the graph shows a similar trend as the experimental data and pattern 8/1 is greater at every angle except 65\degree. Fiber angle affects stability of the thin walls in the test coupons and the ability to deform without buckling. Higher fiber angles resist the formation of buckle waves in the wall, leading to a higher buckling stiffness and strength. Section 1.4.1 illustrates this effect by changing the fiber angle at 1\degree increments and the radial stiffness increases with larger winding angles since the longitudinal $A_{11}$ direction is not equal to the radial $A_{22}$ direction.

Two sample groups, 80\degree 1/1 and 65\degree 8/1, have high standard deviations for both strength and stiffness relative to the other sample groups. The standard deviations are 14.19MPa and 8.11MPa respectively. High deviation of the data from the average decreases the B-basis in order to have 90\% of the data above the value. The coupons all came from one tube, which makes the grouping a sub-sample. A full sample requires data from coupons made from multiple tubes. First, sample size will increase, decreasing deviation, moving the sample’s average closer to the population’s average. Second, variability inherent to the material influence the final composite properties, and multiple sub-samples in the overall sample group accounts for material batch variability. Third, variability occurs during manufacturing related to the tolerances of the machine, wetting consistency of the resin bath, and the changes in ambient temperature and atmosphere. This leads to improving B-Basis reliability and accuracy.
Looking closely at coupons for 65° 1-1 sample group, which were tested on two separate days, produced drastically different stress-strain curves, and shown in Figure 20. Five samples were tested on one day while an additional sample was tested on a separate day. The first five samples show an average strength of 17.74MPa while the sixth sample reached 61.36MPa. The stiffness values of samples one through five averaged 3.48MPa and sample six achieved a maximum at 25.54MPa. The large stress and stiffness coupon could simply be an outlier of the data set, but an alternative explanation would be testing messed up on either of the days, reporting unusable data, require further testing to verify the point. By using the value of just the sixth sample for comparisons to other sample groups, the higher value fits the trends of the strength and stiffness better.

The results in this report compared to results from another study show opposite trends [10]. Their report doesn’t specifically state the fiber stacking sequence, but it seems their tubes are four layers of carbon-fiber with two layers at a positive winding angle and two in at a negative winding angle. This makes the laminate an angle-ply sequence, same as the test coupons in this report. One significant difference between the test coupons is the other study reinforced the bearing surfaces on the tube, reducing the amount of stress seen on the edges and forcing the weakest point in the test coupon to be the tube wall. Reinforcing the bearing surface of the coupons in this project will indicate if failure occurred in the wall or at the bearing surface.
The original goal of testing was to find the material compressive limit, but the small wall thickness, the large diameter of the tube, and the long length of the test coupon resulted in bucking instead. Buckling will always occur at lower strengths compared to the material compressive limit. Samples with smaller lengths would improve the stability of the tubes since buckling is a function of length. Bearing stress is another issue present during testing that was not completely addressed by the fiberglass layer on the test fixture. Reinforcing the bearing surfaces of the test coupon would force failure to only occur in the wall because without reinforcement, the edges of the tube experience higher stresses than the tube walls. Another way to improve testing would be using a different contact layer on the test fixture; a softer and thicker material such as more fiberglass or thin gasket-type rubber are options. A combination of reinforced bearing surfaces on the test sample and softer contact areas on the test fixture would improve testing.

5. Conclusions

1. Based on the B-Basis value, six of the eight winding angle and pattern combinations will work as the structure of a high-powered rocket, with just a single filament wound laminate.
2. Larger winding angles increase maximum buckling stress.
3. Winding patterns with more fiber overlap increase maximum buckling stress.

6. Recommendations

Adding a 90° hoop wrap to a filament winding laminate will improve buckling strength while keeping fibers in the longitudinal direction.

7. References

8. Appendix

8.1. Volume Fractions of each tube fabricated

*Table IV: Volume Fraction, Averages by Winding Angle and Pattern, and Published Material Properties.*

<table>
<thead>
<tr>
<th>Fiber Weight (g)</th>
<th>Final Tube Weight (g)</th>
<th>Volume fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>35° Pattern 1/1</td>
<td>102</td>
<td>119</td>
</tr>
<tr>
<td>35° Pattern 8/1</td>
<td>80</td>
<td>120</td>
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<tr>
<td>50° Pattern 1/1</td>
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<td>66</td>
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<tr>
<td>50° Pattern 8/1</td>
<td>48</td>
<td>97</td>
</tr>
<tr>
<td>65° Pattern 1/1 #1†</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td>65° Pattern 1/1 #2†</td>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>65° Pattern 8/1</td>
<td>37</td>
<td>57</td>
</tr>
<tr>
<td>80° Pattern 1/1 #1†</td>
<td>19</td>
<td>27</td>
</tr>
<tr>
<td>80° Pattern 1/1 #2†</td>
<td>28</td>
<td>46</td>
</tr>
<tr>
<td>80° Pattern 8/1</td>
<td>33</td>
<td>58</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.55</strong></td>
<td></td>
</tr>
</tbody>
</table>

|                  | 35°                  |              | 0.67         |
| fiber density (g/cu.cm) | 1.78              | 50°          | 0.47         |
| epoxy density (g/cu.cm)   | 1.13               | 65°          | 0.54         |
| 80°                  |                      | 0.52         |
| Pattern 1/1        | 0.59                 |              |              |
| Pattern 8/1        | 0.48                 |              |              |

†The beginning stages of manufacturing involved trial and error for tube removal, and the first attempt was unusable as samples, but useful for fiber content statistics. #2 is the second attempt and used for compression testing.

8.2. Individual Sample loads, strengths, and stiffnesses

*Table V: Full Table of Maximum Loads*

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>1/1</td>
<td>8/1</td>
<td>1/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Coupon 1 (N)</td>
<td>462.50</td>
<td>1213.12</td>
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<td>3087.86</td>
</tr>
<tr>
<td>Coupon 2</td>
<td>516.26</td>
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<td>1480.76</td>
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<tr>
<td>Coupon 3</td>
<td>486.71</td>
<td>1589.89</td>
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</tr>
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<td>Coupon 4</td>
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<td>1784.28</td>
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<tr>
<td>Coupon 5</td>
<td>485.06</td>
<td>1317.59</td>
<td>1816.79</td>
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</tr>
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<td>Coupon 6</td>
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<td>Coupon 7</td>
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<tr>
<td>Coupon 9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average (N)</td>
<td>497.80</td>
<td>1391.17</td>
<td>1667.69</td>
<td>3231.41</td>
</tr>
<tr>
<td>Standard Deviation (N)</td>
<td>29.70</td>
<td>158.37</td>
<td>137.43</td>
<td>167.39</td>
</tr>
<tr>
<td>B-basis (N)</td>
<td>396.59</td>
<td>851.43</td>
<td>1199.32</td>
<td>2660.95</td>
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</tbody>
</table>

Average (N) 5024.21

Standard Deviation (N) 6124.51

B-basis (N) 5169.24
Table VI: Full Table of Max Buckling Stress

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
<td>1/1</td>
<td>8/1</td>
<td>1/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Coupon 1 (MPa)</td>
<td>12.48</td>
<td>27.60</td>
<td>43.70</td>
<td>57.48</td>
</tr>
<tr>
<td>Coupon 2</td>
<td>12.91</td>
<td>32.25</td>
<td>45.86</td>
<td>60.26</td>
</tr>
<tr>
<td>Coupon 3</td>
<td>13.05</td>
<td>33.28</td>
<td>49.30</td>
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<td>Coupon 4</td>
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<td>75.37</td>
</tr>
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<td>Coupon 8</td>
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<td>Coupon 9</td>
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<tr>
<td>Average (MPa)</td>
<td>13.43</td>
<td>34.93</td>
<td>49.57</td>
<td>66.53</td>
</tr>
<tr>
<td>Standard Deviation (MPa)</td>
<td>0.91</td>
<td>5.74</td>
<td>5.28</td>
<td>7.52</td>
</tr>
<tr>
<td>B-basis (MPa)</td>
<td>10.32</td>
<td>15.38</td>
<td>31.58</td>
<td>40.89</td>
</tr>
</tbody>
</table>

Table VII: Full Table of Max Estimated Stiffness

<table>
<thead>
<tr>
<th>Winding Angle (°)</th>
<th>±35°</th>
<th>±50°</th>
<th>±65°</th>
<th>±80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern</td>
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<td>1/1</td>
<td>8/1</td>
</tr>
<tr>
<td>Coupon 1 (MPa)</td>
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<td>25.67</td>
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<td>3.72</td>
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<td>1.50</td>
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